Optimal Charging of Vehicle-to-Grid Fleets via PDE Aggregation Techniques

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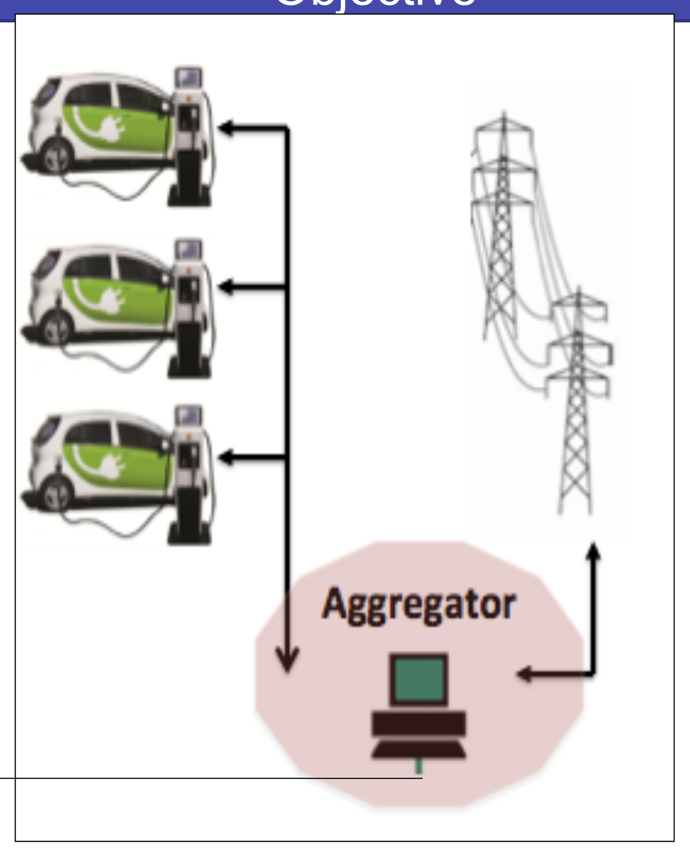
Abstract

Vehicle-to-grid (V2G) capable Plug-in Electric Vehicles (PEV) communicates with the grid, stores energy, and can return energy to the electric grid. We develop a novel modeling approach, which is based on a system of partial differential equations (PDEs), to aggregate and control large populations of PEVs. This framework is very well suited and computationally efficient to address tomorrow's challenge of designing the best strategies for PEV smart charging. First, we validate our model on the Vehicle-to-grid simulator (V2G-Sim). Then we demonstrate that this approach can be used to manage fleets of vehicles and permit a PEV aggregator to participate in the regulation market (provide energy to the grid), and supply PEV drivers with sufficient charge.

Objective



- ◆ Develop an aggregation model for large fleets of electric vehicles
- ◆ Design a smart control algorithm to participate in the regulation market
- ◆ Satisfy drivers' needs for mobility

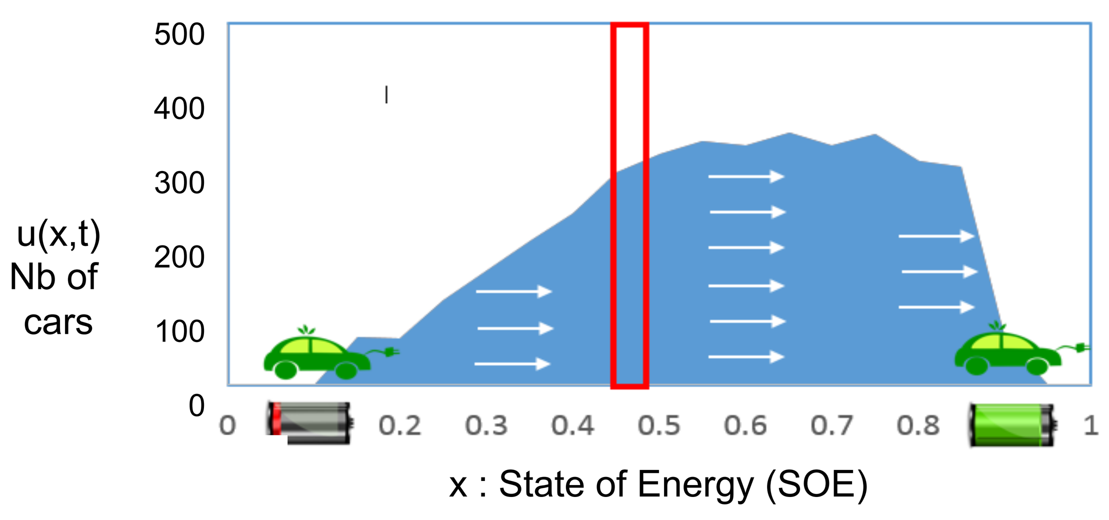
Design a combined smart-charging method for thousands / milions of Electric Vehicles

Prepare the country for the Transportation revolution

Facilitate emergence of V2G aggregators

Modeling aggregation of PEVs

Transport Based model

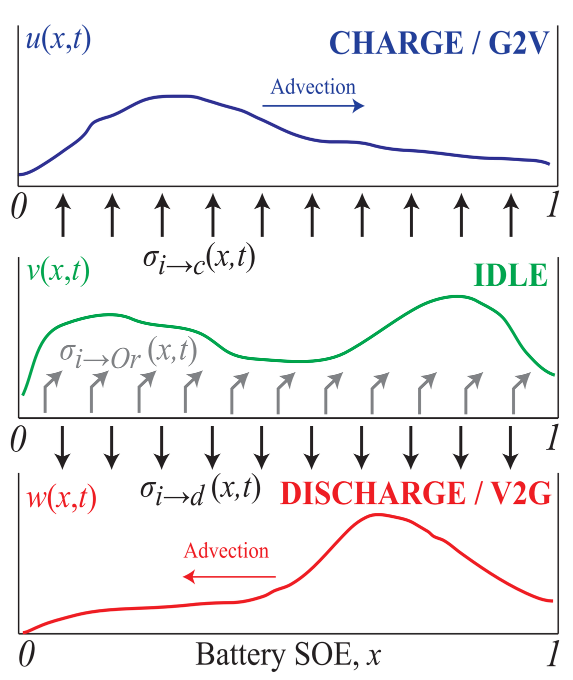


Vehicles charge at rate $q_c(x,t)$

External flows of vehicles (from road) $\cdot\,\sigma_{i\to c}(x,t)dt$.

$$[u(x,t+dt)-u(x,t)]dx = \tag{6}$$
$$q_c(x,t)u(x,t)dt - q_c(x+dx,t)u(x+dx,t)dt + \sigma_{i\to c}(x,t)$$

Vehicle-To-Grid Framework



The aggregator controls the number of vehicles in each state:

- G2V: charging u(x,t)
- Idle v(x,t)
- V2G: discharging w(x,t) (sells energy)

Coupled system of PDEs:

$$\frac{\partial u}{\partial t}(x,t) = -\frac{\partial}{\partial x}[q_c(x,t)u(x,t)] + \sigma_{i\to c}(x,t).$$
$$\frac{\partial v}{\partial t}(x,t) = -\sigma_{i\to or}(x,t) - \sigma_{i\to c}(x,t) - \sigma_{i\to d}(x,t),$$
$$\frac{\partial w}{\partial t}(x,t) = \frac{\partial}{\partial x}[q_d(x,t)w(x,t)] + \sigma_{i\to d}(x,t).$$

Validation

V2G-Sim is an agent-based simulator that models the driving and charging behavior of individual PEVs. It is developed by the Grid Integration Group at LBNL.

Data: 17805 vehicles in California during a week-day from National Household Travel Survey (NHTS) 2009. The fleet is composed of Nissan Leaf cars.

2 control cases : Open-Loop / Discharge during electricity peak hours

2 charging rates : L1 chargers (1.44kWh) / L2 chargers (6.6kWh)

$$e(t) = \frac{\|(u+v+w)_{PDE}(\cdot,t) - (u+v+w)_{V2Gsim}(\cdot,t)\|_2}{\|(u+v+w)_{V2Gsim}(\cdot,t)\|_2}$$

Case	Mean error
Open Loop L1 charger	1.1%
Open Loop L2 charger	2.3%
V2G control L1 charger	0.2%
V2G control L2 charger	2.8%

Optimal control of vehicles

Choose the best flows between G2V, V2G and Idle (minimize aggregator cost) such that: every driver is satisfied and the aggregator supplies energy to the regulation market. Main assumptions:

- Electricity cost C_{elec}, departures *Dep*, regulation power P^{des} are known one day in advance.
- Cars must depart with minimum SOE X_{dep}.

Control Formulation

$$\min_{u,v,w,Dep} \Delta t\, \Delta x \sum_{n=0}^{N}\sum_{j=0}^{J} C^n_{elec} q^n_j w^n_j$$

subject to

$$[u+v+w]^{n+1} + \frac{Dep^{n+1}}{\Delta x} = M_c u^n + M_d w^n + \frac{Arr^{n+1}}{\Delta x}$$

$$u^n_0 = 0, \quad v^n_J = 0,$$
$$u^0_j = u_{0,j}(j\Delta x),\ v^0_j = v_{0,j}(j\Delta x),\ w^0_j = w_{0,j}(j\Delta x),\ \forall j,$$

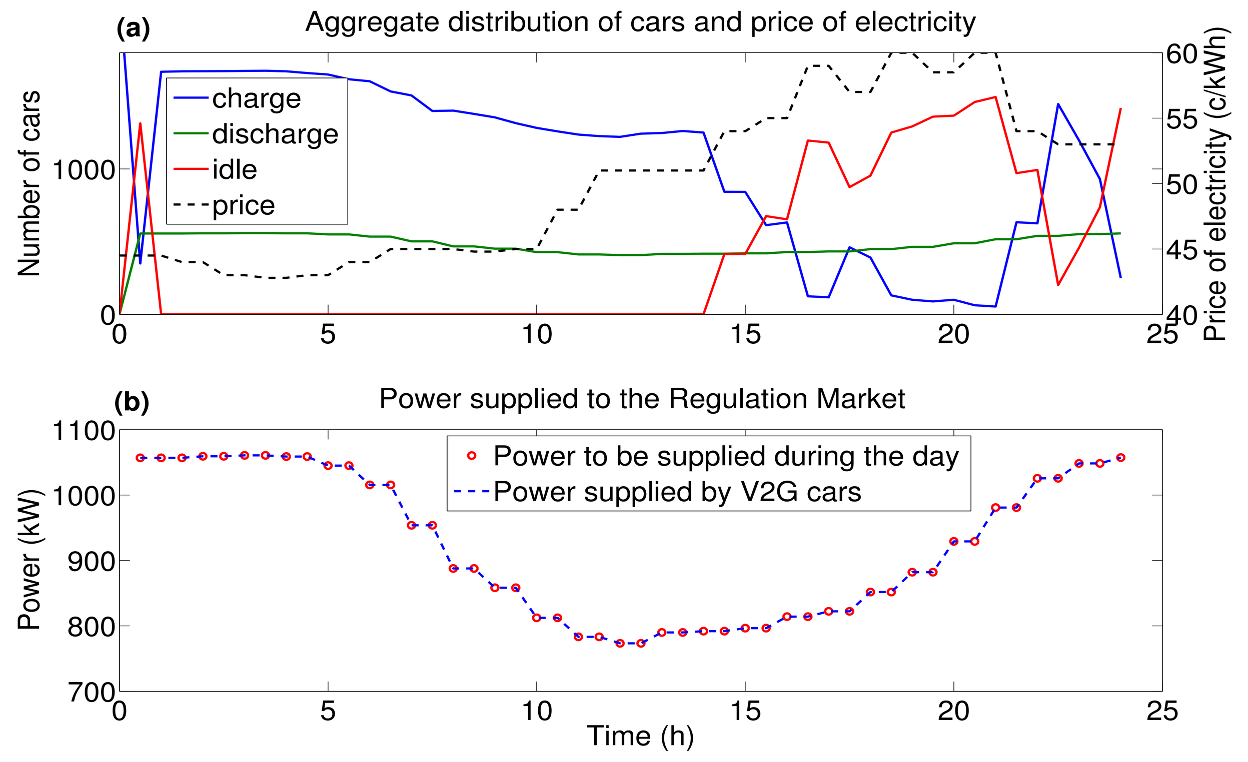
$$u^n, v^n, w^n, Dep^n \geq 0,$$
$$u^n_j = 0\ \forall\ j \geq X_{max}\cdot J$$
$$v^n_j = 0\ \forall\ j \leq X_{min}\cdot J$$
$$w^n_j = 0\ \forall\ j \leq X_{min}\cdot J$$

$$\Delta x \sum_{j=0}^{J} q^n_{d,j} w^n_j \geq P^{des,n}$$
$$\sum_{j=X_{dep}\cdot J}^{J} Dep^n_j = Dem^n$$
$$\Delta x \sum_{j=X_{dep}\cdot J}^{J} u^N_j + v^N_j + w^N_j \geq N_{min}$$

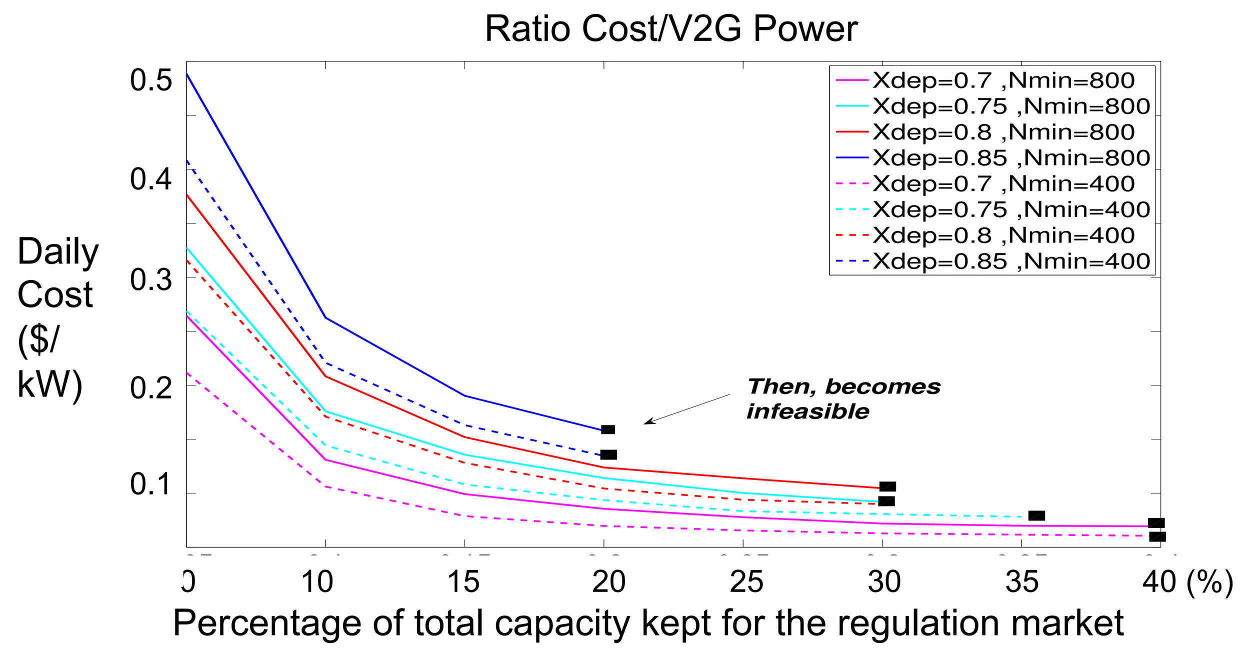
After discretization of PDEs, we formulate the Linear Program above, and solve it using a LP solver.

- Time horizon: 24h
- Number of cars: 2300 (taken from NHTS)
- Charging rate: 1.9kWh

Result and sensitivity analysis



- ➢ The aggregator computes flows between idle and G2V: EVs charge when price of electricity is lower.
- ➢ V2G cars supply required energy to the grid.



- ➢ The optimization allows economies of scale: cost per produced kW decreases as required energy increases.

Conclusion

- ◆ The model is validated, PDE techniques are well suited for large populations of Evs.
- ◆ The optimization program allows EV aggregators to optimize their cost while participating to the regulation market and satisfy every driver.
- ◆ **How can we integrate grid constraints into this framework?**

References

[1] S. Bashash and H. Fathy, "Transport-based load modeling and sliding mode control of plug-in electric vehicles for robust renewable power tracking," IEEE Transactions on Smart Grid, vol 3, no. 1, pp. 526–534, March 2012.

[2]W. Kempton and S. E. Letendre, "Electric vehicles as a new power source for electric utilities," Transportation Research Part D: Transport and Environment, vol. 2, no. 3, pp. 157–175, 1997.

[3] http://v2gsim.lbl.gov

[4] S. J. Moura, V. Ruiz, and J. Bendsten, "Observer design for boundary coupled pdes: Application to thermostatically controlled loads in smart grids," in 52nd IEEE Conference on Decision and Control, Florence, Italy, 2013